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ABSTRACT

This study concerns ground strains that result from spatially variable ground motions unrelated to ground failure. Prior empirical work shows a dependence of peak ground strain (PGS) on peak ground displacement (PGD) but is applicable only for weak motions (PGD < 10 cm). Prior semi-empirical work, in which strains were evaluated from simulated ground motions that preserve the coherency, Fourier amplitude variability and wave passage observed in array recordings, found a similar dependence of PGS on PGD but also a significant dependence on separation distance of observation points. Here we describe a procedure to calculate PGS between pairs of stations in an array to test the separation dependence of PGS. The Lotung LSST array was selected due to its closely spaced stations (6 to 85 m) and large number of recordings. The PGS estimated from station pairs from 11 events illustrate that the distance dependence of PGS is statistically significant, with PGS increasing as separation distance decreases.

INTRODUCTION

Transient ground surface strains are important in the response of buried or sensitive structures (i.e. pipelines or poorly reinforced concrete foundation slabs) shaken by earthquakes. The spatially variable ground motions (SVGM) that give rise to transient strains are partly, but not fully, explained by wave passage effects. Additional sources include incoherent waves and spatially variable site response. Ground strains are typically quantified by a peak value (peak ground strain, PGS), and empirical models have been developed to estimate PGS from the amplitude of shaking. A semi-empirical model by Ancheta et al. (2008) found PGS to also be sensitive to the separation distance of observation points. This study investigates whether that semi-empirical finding is observed in array data.

PREVIOUS STRAIN MODELS

Empirical models for estimation of PGS have been developed by Abrahamson (2003) and Paolucci and Smerzini (2008). The Abrahamson (2003) model estimates the ratio of PGS to peak horizontal ground displacement (PGD) as the sum of independent contributions from wave passage, variable site amplification, and incoherency:

$$\frac{PGS}{PGD(cm)} = \frac{e^{(5.8-0.69M)}}{V_{app}} + 3.0\times10^{-5} + 3.0\times10^{-5} \qquad (1)$$

where M = moment magnitude and V_{app} = apparent shear wave speed in basement rock, taken as 2.5 km/s.

Paolucci and Smerzini (2008) estimated PGS from a spatially interpolated 2-D surface displacement field evaluated from array recordings. The interpolated displacement field enables evaluation of the maximum PGS regardless of azimuth. This strain was called the maximum highest principal strain or HPS_{max} by Paolucci and Smerzini (2008). Their data and proposed model are shown on Figure 1.

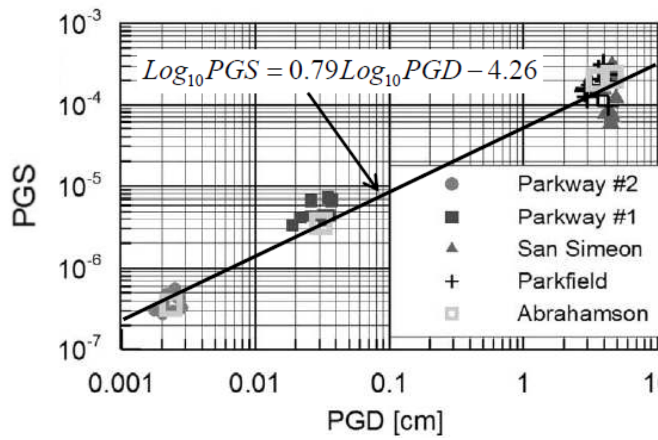

Fig. 1) Data and model for HPS_{max} from Paolucci and Smerzini (2003) and model estimate from Abrahamson (2003). Figure Modified from Paolucci and Smerzini, (2008)

Ancheta et al. (2008) developed a model that is semi-empirical in the sense that SVGMs are simulated using empirical models for coherency, Fourier amplitude variability, and wave passage from Abrahamson (1992). For each of several 'seed' records, many 'child' simulated motions were generated at various separation distances from the seed. PGS was calculated for each seed-child pair as the ratio of peak differential displacement to separation distance. The "columns" of data points in Figure 2 correspond to the PGS values computed for a given seed. Repeating for many seeds having various peak ground displacements (PGD), and various seed-child separation distances (ξ), enables the model fits shown in Fig. 2 to be developed. Note two differences from the empirical models: (1) PGS saturates at high amplitudes and (2) PGS increases as ξ decreases.

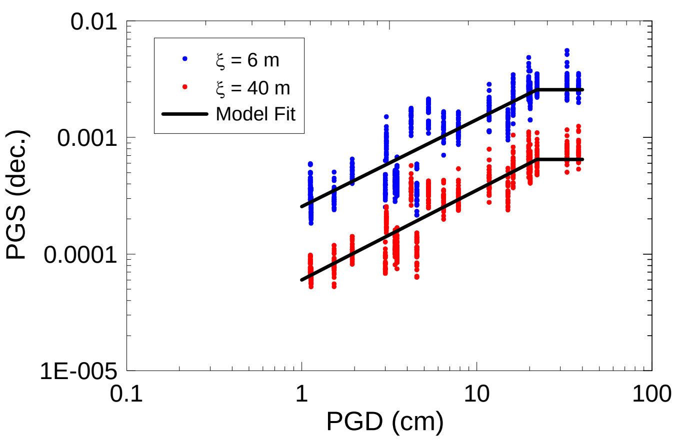

Fig. 2. Predicted PGS for a separation distance of 6 and 40 m along with individual model fit (modified from Ancheta et al. 2008)

An inconsistency between the models is how PGS is defined. Paolucci and Smerzini (2008) define PGS as the maximum strain relative to all potential azimuths, which they observed to be aligned with the source-site ray path azimuth. Ancheta et al. (2008) and Abrahamson (2003) estimated PGS as the maximum strain between two station points along an arbitrary azimuth corresponding to that of a line drawn between the instruments. This arbitrary azimuth may be different for each station pair in an array. However, since the Paolucci and Smerzini (2008) and Abrahamson (2003) models are generally consistent (as shown in Figure 1), the representation of strain as HPS_{max} or PGS on arbitrary azimuths may not be critical. For the present study we estimate PGS on arbitrary azimuths defined by the array station configurations.

The objective of this study is to test whether the ξ-dependent strains found in the semi-empirical work and shown in Fig. 2 are also observed from direct analysis of array data. The strain data will also be used to validate the log-linear relationship between PGS and shaking amplitude (PGD).

DATA SELECTION

We utilize data from the Large Scale Seismic Test (LSST) array located near Lotung, Taiwan. The LSST array was selected due to the large number of event recordings, small station separations (6 to 85 m), and the relatively uniform layering of the underlying geology. This study uses the LSST surface array consisting of 15 three-component force balanced accelerometers configured as shown in Figure 3. Additional details on the array can be found in Liu and Yeh (1985).

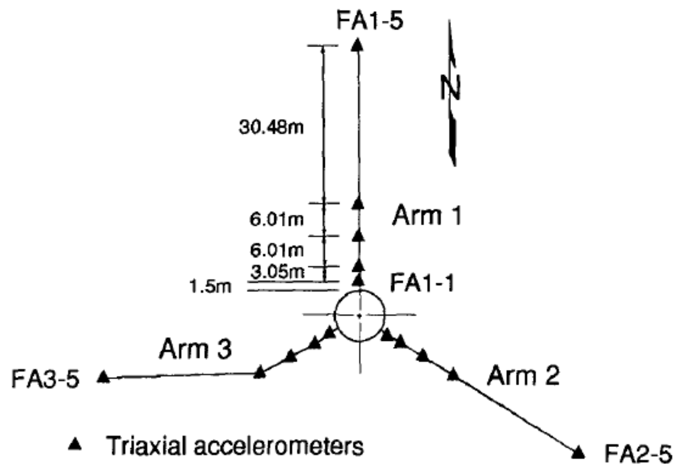

Fig. 3. Station configuration of the LSST array (Abrahamson, et al., 1991).

Table 1 lists eleven events that were selected for their range of magnitudes and maximum peak ground displacement (PGD). All surface stations were used except FA1-1, FA2-1, and FA3-1 as they were found to be affected by the response of the test structure in the middle of the array (Abrahamson 1992).

Table 1. Selected LSST Events (data from Abrahamson et al., 1991)

Event Name	Date	M	Max. PGD (cm)
Event 2	10/26/85	4.6	0.12
Event 3	11/07/85	4.7	0.04
Event 4	1/16/86	6.0	4.5
Event 5	3/29/86	3.9	0.09
Event 6	4/08/86	4.3	0.14
Event 7	5/20/86	6.4	5.3
Event 10	7/19/86	3.7	0.04
Event 12	7/30/86	5.6	1.6
Event 13	7/30/86	-	0.58
Event 14	7/30/86	4.1	0.11
Event 16	11/14/86	7.8	7.1

ESTIMATION OF STRAIN

In this section, we describe our procedure for estimating peak horizontal extension/compression ground strains from array station pairs. Figure 4 illustrates the procedure applied to two station pairs with separation distances ξ = 6 and 43 m. We first remove the wave passage lag and define the S-wave window. Figures 4a-b show the s-window of station pairs following lag removal. Next a baseline correction is applied and acceleration is integrated to displacement, with the results shown in Figures 4c-d. Finally, differential displacements between pairs are calculated with the results in Figure 4e. Additional details of each step are presented below.

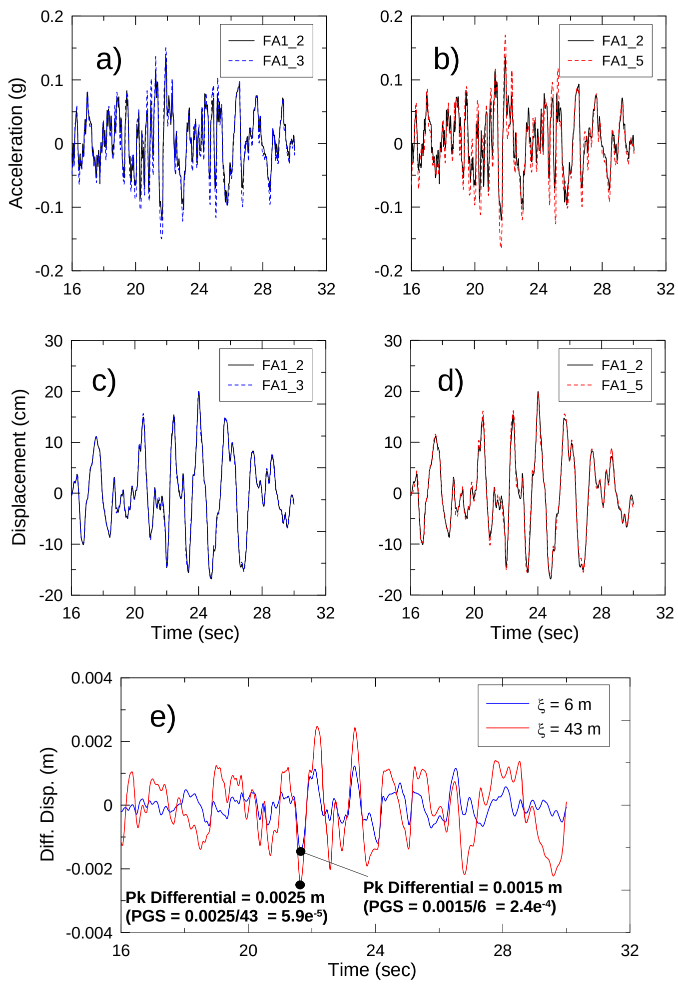

Fig. 4. Schematic overview of strain calculation on two separation distance pairs (6 m and 43 m). Parts a) and c) represent the 6 m pair and b) and d) represent the 43 m pair.

In order for the strains to be comparable to those evaluated in Ancheta et al. (2008), PGS is estimated using the S-wave window portion of the records with the wave passage effects removed. The S-wave windows selected for each event were similar to those of Abrahamson (1992). The removal of the time delay from wave passage is accomplished by aligning each station in time with respect to a single reference station (FA1-2). We align by shifting each station relative to the reference station by the number of time steps associated with the maximum cross correlation.

Next the motions are rotated and baseline corrected. The rotation is done so that one of the horizontal components of motion is aligned with the azimuth of a line drawn between stations. Differential displacements along this line correspond to SVGM in extension and compression. Because of the three-arm layout of the LSST array, the azimuths corresponding to various station pairs do not match. After rotation, all stations in each event were processed with the same baseline correction procedure to remove the long period noise from digital data. The correction procedure includes a high-pass filter of the acceleration and the removal of the mean offset from zero in the velocity. A single highpass corner frequency (f_c) was selected for each event so that the same correction was applied to all stations. The f_c value was selected based on the signal to noise ratio (SNR) of the S-wave window. The SNR was estimated by comparing the Fourier amplitude spectra of the S-wave window to the spectra of pre-event noise. The range of selected f_c values was 0.3 to 1.5 Hz.

Strains are then calculated by normalizing the differential displacement between station pairs by the separation distance. The maximum value of strain within the S-wave window is defined as the PGS. A summary plot of PGS values plotted as a function of PGD for all events is shown in Figure 5. The spread of the data is larger than that shown in Figure 2. We believe this results in part from our sampling of strains from many station pairs for each earthquake event, giving rise to intra-event variability along with the inter-event variability associated with using data from multiple earthquakes. In contrast, Paolucci and Smerzini (2008) identify a relatively small number of peak strains from each event, hence their data scatter may not fully capture intra-event variability.

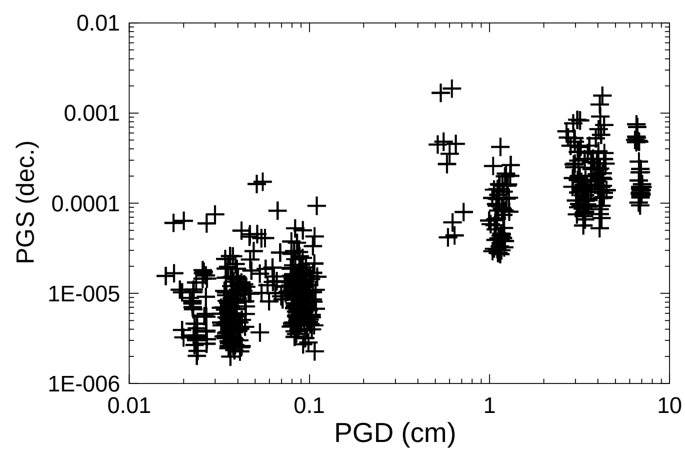

Fig. 5. Summary plot of all PGS-PGD pairs for all selected LSST events

DISTANCE DEPENDENCE VALIDATION

To investigate possible distance dependence, strains inferred from the LSST array are separated into distance bins. Each subset is separately fit with a linear model between PGS and PGD with the results in Figure 6. Although there is significant overlap in the data spread for each distance bin, the fit lines appear to be distinct and to suggest systematic increase of strain with decreasing ξ. Visually, the distance dependence seems to become weaker as ξ increases.

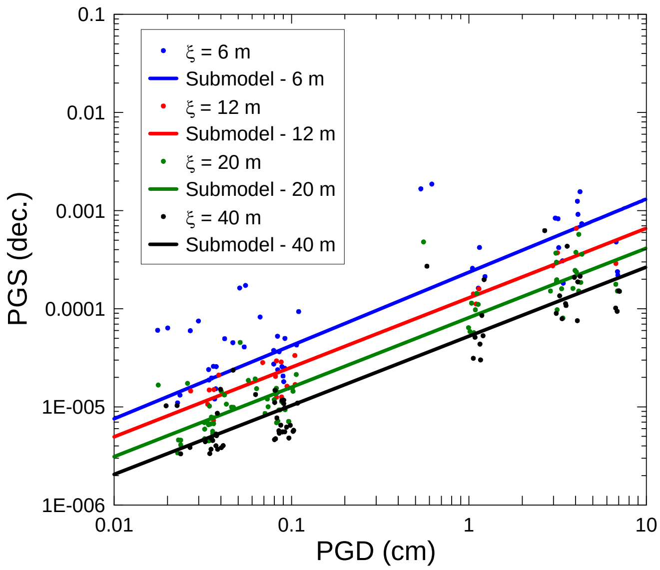

Fig. 6. PGS estimated from the 11 events plotted in distance bins along with a least squares regression fit (dashed line).

To evaluate the degree of difference between distance bins, F tests are performed on the submodels. The F statistic tests whether individual models with separate data sets or a single combined model describe the collective data better (Cook and Weiberg, 1999). For the present application, the single combined model would be a single regression line drawn through a collection of data having multiple ξ values. The individual models are those shown in Fig. 6. Strain residuals between data and models can be calculated for each data point, and residual sum of squares (RSS) calculated for each model. Referring to RSS for the combined model as RSS_f and RSS for two individual models as RSS_1 and RSS_2, the F statistic is calculated as (Cook and Weiberg, 1999):

$$F = \frac{\left(RSS_f - \left(RSS_1 + RSS_2\right)\right) / \left(\left(df_1 + df_2\right) - df_f\right)}{\hat{\sigma}^2} \quad (2)$$

$$\hat{\sigma}^2 = \frac{RSS_1 + RSS_2}{N_f - \left(df_1 + df_2\right)} \quad (3)$$

where df_i is the degree of freedom of the regression fit (two in this case) and N_f is the number of data points in the full model. The F value is compared to the F distribution to give a corresponding significance level (p). We consider the submodels to be significantly distinct if the p-value is low (< 0.05). Table 2 summarizes the F test results.

Table 2. F-Test Summary

Submodels	F	p-value
ξ = 6-12 m	-1.63	0
ξ = 6-20 m	15.2	0.0037
ξ = 6-30 m	32.4	0.00089
ξ = 6-40 m	25.2	0.00145
ξ = 6-60 m	57.5	0.00029
ξ = 6-90 m	17.5	0.0029

Table 2 shows that each of the considered pairs are significantly distinct based on the above criteria. This suggests that the ξ-dependence of the data is significant from a statistical perspective.

We also note that the average slope of the submodels (0.72 dec/cm) agrees with that of the previous empirical work (e.g., the value of 0.79 in Figure 1 and an average of 0.75 in Figure 2).

CONCLUSION

In this paper we present data from the Lotung LSST array that shows that extension/compression ground strains scale both with the amplitude of ground shaking (as represented by PGD) but also with separation distance (ξ). The distance dependence is similar to that identified previously from the semi-empirical procedure of Ancheta et al. (2008). We also demonstrate significant variability in strains both within a given event (intra-event variability) and from one event to another (inter-event variability). Both significantly contribute to overall variability.

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